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Visual sensitivity to irregularities in periodic tiling patterns

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A single experiment was conducted to evaluate the sensitivity of human vision to irregularities in regular (repetitive) patterns that tile the plane; mathematicians have been investigating such patterns (tilings) for hundreds of years. The stimulus patterns in the current study were composed of obliquely oriented line segments and strongly resemble patterns used in traditional art. In the experiment, the pattern density was manipulated as well as the magnitude of pattern alteration. Signal detection methodology was used, such that the observers' task was to indicate for each presented pattern whether it was perfectly regular or it had been altered such that the periodicity was broken. The obtained results indicate that human observers are moderately sensitive (overall d' value was 1.76) at detecting violations of the periodicity of regular patterns that tile the plane. High performance (d' values greater than 2.0) only occurs, however, when pattern elements repeat over small spatial scales.

Mathematicians have long been interested in patterns that tile the plane. For example, consider the work of Johannes Kepler, the sixteenth- and seventeenth-century mathematician and astronomer. In his 1619 book *Harmonices Mundi Libri V*, Kepler[1] discusses regular patterns that tile the plane and provides some excellent examples. In one really interesting example (in the plates following page 58), he shows how it is possible to tile the plane using a combination of pentagons, upside down pentagons, decagons, and stars. The left panel of Fig. 1 shows a colorized version of Kepler's tiling, while the right panel shows the first author's own tiling of the plane using a single arbitrarily shaped 18-sided polygon. Determining which geometrical patterns will tile the plane is a fascinating problem in mathematics[1–5]. The famous experimental psychologist Fred Attneave (well known for applying information theory to the study of visual perception; for example, see[6]) developed an algorithm that produced regular patterns that tile the plane[7] -- an example of such a pattern generated by his method is shown in the left panel of Fig. 2. Attneave's procedure generates visual patterns that strongly resemble traditional art[8–10] in both Central Africa (the Kuba people, see right panel of Fig. 2) and eighth-century Scotland (i.e., Pictish art).

Vision scientists have long known that some deviations from uniformity/regularity are easy to detect, while others are not[11–16]. Treisman[15,16], for example, has demonstrated that differences in color, orientation, and curvature are especially salient and detectable. As an example of the human sensitivity to collinearity (and deviations from collinearity), consider the experiment conducted by Norman, Shapiro, Sanders, and Sher[12]. They used stimuli similar to those depicted in Fig. 3. The background in both panels consists of randomly oriented dotted line segments. In both panels the homogeneity of the background is disrupted by the inclusion of a small rectangular region where the dotted "line segments" are no longer collinear but have been bent at an angle. When the bend angle is sufficiently large, it is easy to spot the deviant texture elements forming a rectangle (for example, in the right panel of Fig. 3). In contrast, if the deviation from regularity (e.g., deviation from collinearity) is too small, then perceptual segregation will not occur (e.g., it is quite difficult to spot the vertically oriented rectangle in the left panel of Fig. 3; finding the object requires scrutiny). In their 2021 study, Norman et al. found that younger adults (mean age was 19.0 years) needed a bend angle of 32 degrees in order to reliably discriminate object shape (i.e., determine whether the texture-defined shape was a horizontal or vertical rectangle) for stimulus displays similar to those shown in Fig. 3. Other deviations from regularity are highly visible and produce perceptual segmentation, such as changes in texture element lightness and size (e.g., see Beck[14]). In Experiment 1 of Beck[14], a uniform field of alternating light and dark texture elements (light-dark-light-dark...) presented against a black background was reversed in a central region (dark-light-dark-light...), resulting in good perceptual segmentation when there were small separations between texture elements; for this stimulus, Beck's observers provided an average segmentation rating of 4.73 (where a rating of 1 indicated no perceptual segmentation between central and surrounding regions and a rating of 5 indicated that the central region stood out strongly against the background). Similar results occurred when Beck manipulated texture element size instead of lightness.

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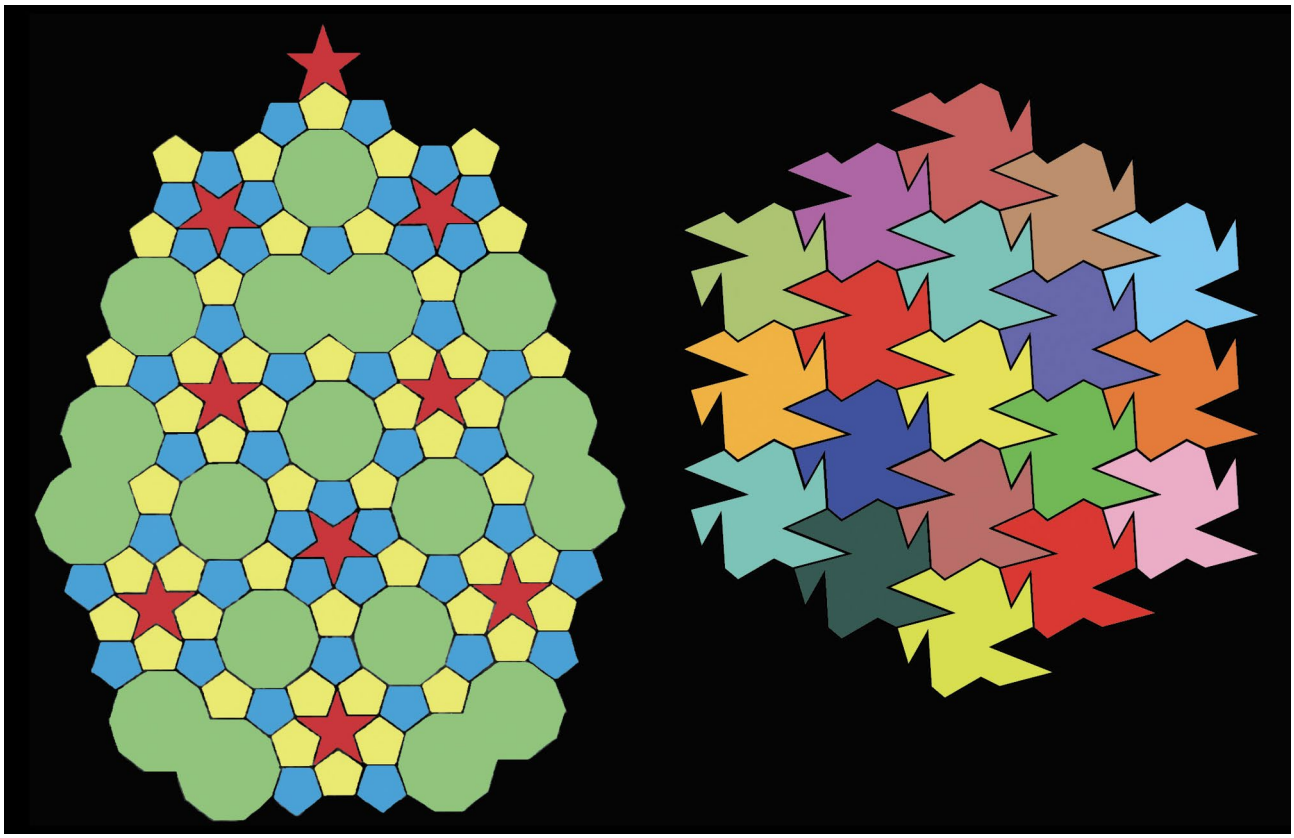

Fig. 1. Tilings of the plane. The left panel shows a colorized version of a tiling originally published by Johannes Kepler in his 1619 book *Harmonices Mundi Libri V*; this color version was created by the first author (J.F.N.). The right panel shows tiling of the plane by an 18-sided polygon also created by the first author (J.F.N.).

Fig. 2. The left panel shows an example of a periodic tiling of the plane using an algorithm developed by Fred Attneave in 1959[7]. This tiling was created by the first author (J.F.N.). The right panel shows a portion of a textile produced by the Kuba people of Central Africa. This photograph is in the public domain and was licensed with a Creative Commons Zero (CC0) license from the Cleveland Museum of Art; the original public domain photograph can be found at https://www.clevelandart.org/art/1992.102.

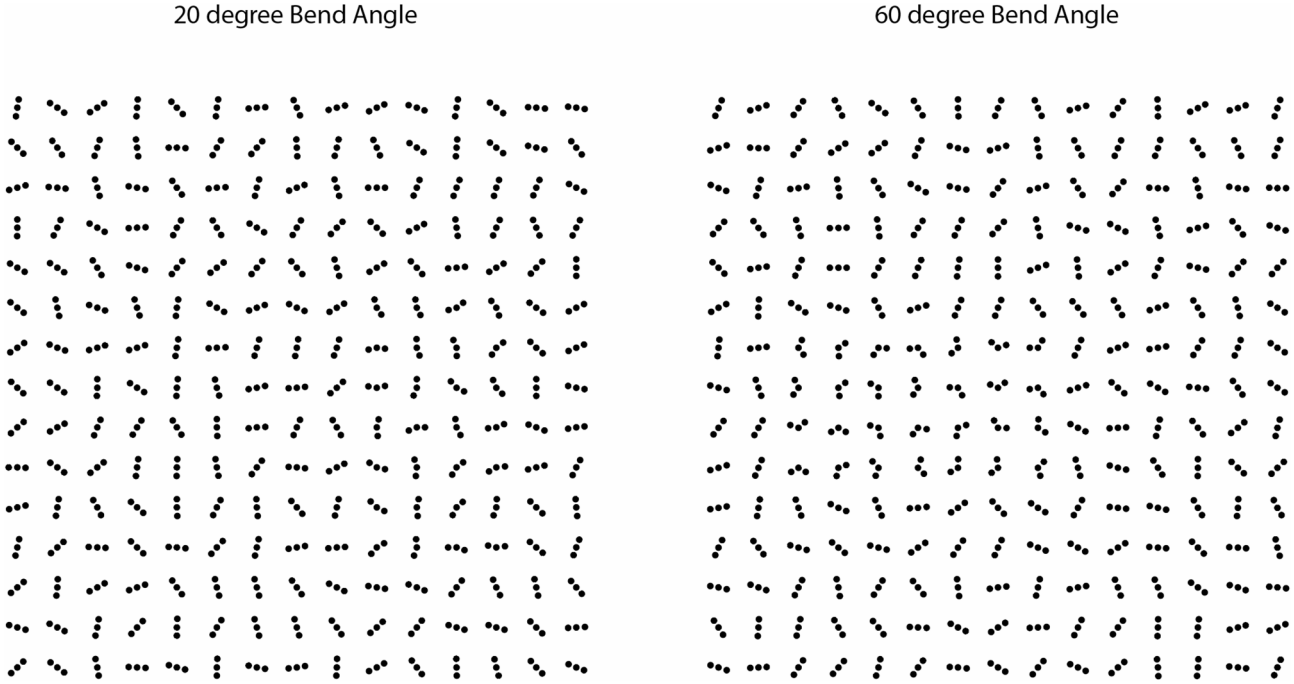

Fig. 3. Texture-defined objects similar to those used by Norman, Shapiro, Sanders, and Sher[12]. A rectangle formed from deviant texture elements (different from texture elements in the background) is difficult to see in the left panel, but is readily visible in the right panel. This figure was created by the first author (J.F.N.).

We already know from existing research spanning decades (for example, the research described in the previous paragraph[11–16]) that human observers are sensitive to some particular deviations from uniformity/regularity across a variety of patterns. At the same time, it is also true that there are many other textural and stimulus irregularities that are simply not detectable to human vision (e.g., see the work of Julesz and colleagues[17–19]). This is an interesting dichotomy -- some stimulus deviations are highly salient to human vision while others cannot be seen at all, even though they are physically present. At the present time, we know essentially nothing about the detectability of deviations from perfectly regular patterns that tile the plane (e.g., those created by Attneave[7] and which are shown in the left panel of Fig. 2). The primary purpose of the current experiment was to remedy this lack of knowledge. How much pattern element alteration is needed to visibly violate the periodicity of patterns that tile the plane? Will small inhomogeneities in periodic patterns (that tile the plane) be highly detectable? The answer at present is essentially unknown. Given that Attneave's periodic patterns[7] consist of oriented line segments and the fact that orientation is considered a fundamental feature for vision (e.g., see Treisman[15,16]), it seems likely that observers' ability to detect irregularities in such patterns will be good. Norman et al.[20] found that inhomogeneities (i.e., irregularities) in the distribution of surface features are important for the visual perception of 3-D shape -- the goal of the current study was to determine whether the same sensitivity occurs with respect to periodic visual patterns that tile the plane.

Method

Apparatus

An Apple M1 iMac (with a 24-inch retina 4.5 K display) was used to generate the experimental stimuli and to record the observers' judgments after each trial.

Experimental stimuli

The stimulus display on any given trial was either a "regular" pattern generated by Attneave's (p. 504) algorithm[7], or one of Attneave's patterns that had been altered by having some percentage of its constituent line segments rotated by 90 degrees (thus breaking the periodicity). The patterns were of two types: low density (composed of 324 oriented line segments) or high density (composed of 1296 oriented line segments). Two representative regular (i.e., periodic) patterns are shown in Fig. 4, while six representative altered patterns are shown in Fig. 5. On each trial, one of such patterns was presented for either 0.5, 1.0, or 1.5 s. The patterns were viewed through a circular aperture (diameter was 9.3 degrees visual angle) which was itself set within a 1,000 by 1,000 pixel window (subtending 13.2 × 13.2 degrees visual angle). The viewing distance was 100 cm.

Procedure

Each observer participated in a total of six experimental conditions formed by the orthogonal combination of three perturbation magnitudes (9, 18, and 27% of the patterns' constituent line segments were rotated by 90 degrees, as earlier described; compare Figs. 4 and 5) and two texture densities (patterns composed of 324 or

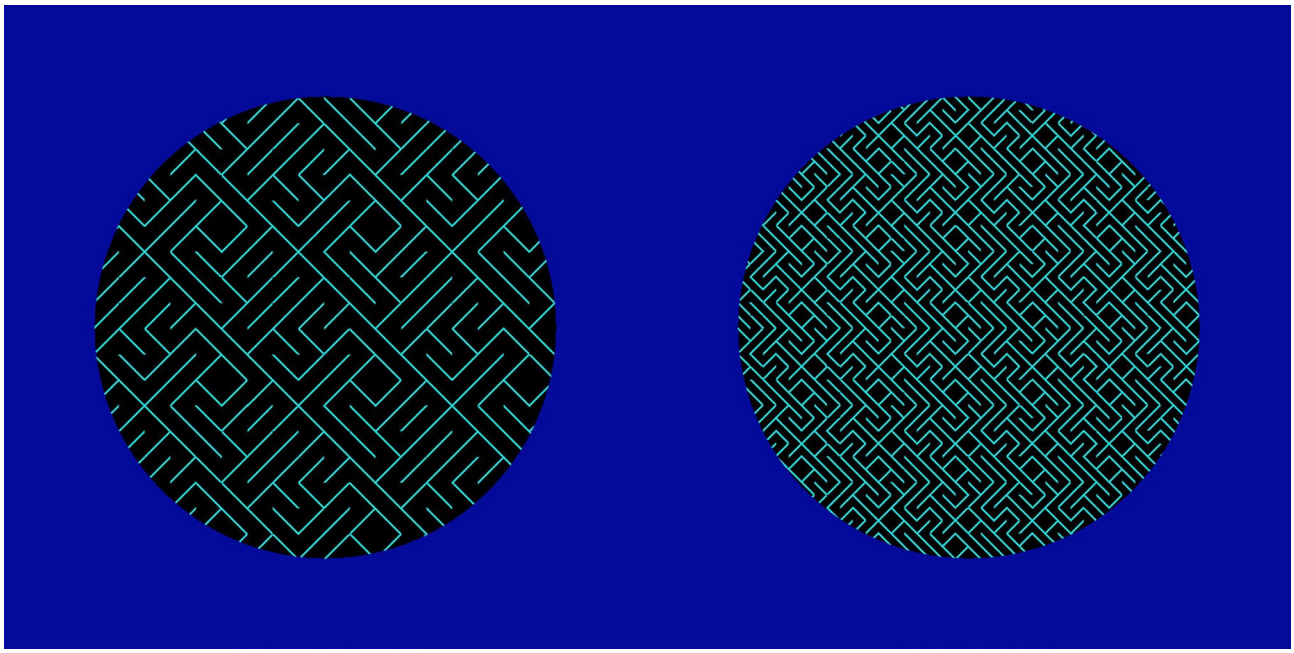

Fig. 4. Examples of experimental stimuli. Two representative regular (i.e., periodic) patterns are shown. The left stimulus is an example of a low density pattern, while the right stimulus is an example of a high density pattern.

1296 oriented line segments). While the manipulation of perturbation magnitude and texture density was within subjects, the manipulation of stimulus duration (0.5, 1.0, or 1.5 s) was between subjects. For each observer, a separate block of forty trials (20 trials for regular patterns and 20 trials for altered patterns, all presented in a random order) was conducted for each of the six conditions. The order of the low-density and high-density blocks of trials was counterbalanced across observers. Within the low-density or high-density blocks, the order of the low (9%), moderate (18%), and high (27%) magnitudes of pattern alteration was randomly determined for each observer. The observers' task for each block was simply to indicate after each trial whether a regular or altered pattern had been presented. At the end of the experiment, each observer had made a total of 240 judgments. No feedback about performance was provided to the observers until after they had completed the experiment.

Observers

The observers were 21 adults from the local community. One group of seven observers viewed the stimulus patterns for 1.5 seconds, one group of another seven observers viewed the stimulus patterns for 1.0 second, while the final remaining group of seven observers viewed the patterns for 0.5 seconds (the assignment of observers to groups was random). In our previous pattern experiment[21], the stimulus duration was 1.25 seconds. Since no previous experiment has ever systematically evaluated observers' ability to detect deviations in periodic patterns that tile the plane, the stimulus durations needed to obtain good performance (e.g., d' values greater than 1.0 or 1.5) were entirely unknown. Therefore, we used two durations (1.5 & 1.0 s) that bracketed the single duration used in our previous pattern experiment (1.25 s), as well as one shorter duration (0.5 s). The shortest duration (0.5 s) was included only to determine whether the task was doable with any degree of accuracy at such a short duration. In our previous study of visual patterns[21], a total sample size of 18 observers gave sufficient power to detect within subjects' effects (in that experiment, magnitude of visual noise and pattern complexity, see Fig. 2 of Norman, Graham, & Eaton[21]). Because 18 observers were sufficient to detect within-subjects effects in our previous pattern experiment, we decided to recruit a similar number of observers in the current study. The 21 observers were completely naïve with regards to the purposes and details of the experiment; they knew nothing other than the obvious fact that they were being asked to make judgments about whether the depicted stimulus patterns were periodic (repeated perfectly across space) or not. The observers had excellent visual acuity: the acuity of the observers (measured with a Precision Vision ETDRS 2195 eyechart) was −0.09 LogMAR (log minimum angle of resolution). The study was approved by the Institutional Review Board of Western Kentucky University, and each observer signed an informed consent document prior to testing. Our research was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Results

Various aspects of the observers' results are shown in Figs. 6 and 7. We evaluated the observers' pattern discrimination ability in terms of d', the perceptual sensitivity measure of signal detection theory[22,23]. The d' values were then subjected to a three-way split-plot analysis of variance (ANOVA). First, there was a large effect

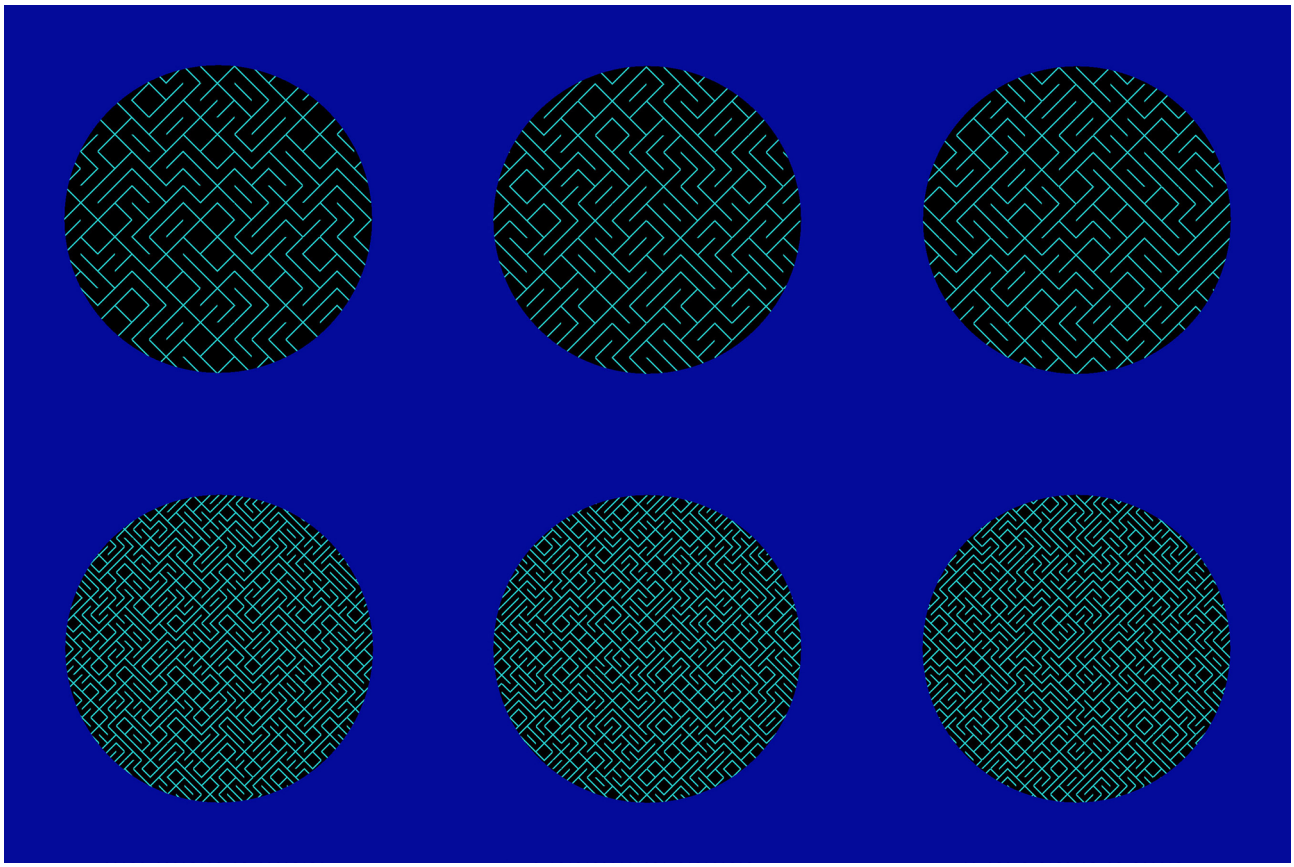

Fig. 5. Examples of experimental stimuli. Six representative altered patterns are shown. The top row shows examples of low density altered patterns, while the bottom row shows examples of high density altered patterns. Within any given row, as you progress from left to right the pattern alteration magnitude (described in text) increases from 9.0 to 18.0 to 27.0% of the pattern's constituent elements. Because the pattern alteration magnitude increases from left to right, as one progresses rightward from the left it becomes more and more difficult to detect the remaining periodic structure.

of pattern density ($F(1,18) = 34.5$, $p = .000015$, $\eta^2_p = 0.66$). There was also a significant effect of pattern alteration magnitude ($F(2,36) = 3.34$, $p < .05$, $\eta^2_p = 0.16$), although it was smaller in magnitude. The density x alteration magnitude interaction was not significant, however ($F(2,36) = 1.8$, $p = .17$, $\eta^2_p = 0.09$). The significant main effects of pattern density and pattern alteration magnitude can be seen in Fig. 6. The potential effect of stimulus duration (0.5, 1.0, and 1.5 s) was not significant ($F(2,18) = 2.3$, $p = .13$, $\eta^2_p = 0.2$). The results for all individual observers in all experimental conditions are shown in Fig. 7. It is true that the observers' average discrimination performance numerically increased as the stimulus duration increased. Figure 7, however, also reveals the extensive amount of inter-observer variability in performance that occurred *within* each duration condition. An inspection of Fig. 7 indicates why the potential effect of stimulus duration was not significant. There were many observers in the 0.5 s duration condition that outperformed many other observers in the 1.0 s duration condition; likewise, there were many observers in the 1.0 s duration condition that outperformed many observers in the 1.5 s condition (and there were many observers in the 0.5 s condition that outperformed many others in the 1.5 s condition). All other potential effects (other 2-way interactions and the 3-way interaction) were not significant.

Discussion

In 1996, Rao and Lohse[24] conducted a most fascinating and important experiment; their goal was to identify (p. 1649) "what textural features are important in texture perception" and to work towards creating a texture naming system. Rao and Lohse presented their observers with 56 textured images. The observers were asked to sort the images into groups, and they were given no explicit criteria by which to judge similarity. Hierarchical cluster analysis and multidimensional scaling (MDS) were then used to identify clusters of perceptually similar textures. Figure 8 illustrates three textures, each of which would belong to one of the eight clusters (A-H) of textures identified by Rao and Lohse. The marble texture (left) would belong to cluster B, while the brick and hexagonal tile textures would belong to clusters G and H, respectively. Cluster B textures, such as the marble texture, possess high randomness and low regularity/repetitiveness. In contrast, clusters G and H are highly regular and repetitive; what distinguishes clusters G and H is directionality (notice that the brick texture, while repetitive and regular, possesses directionality; the hexagonal texture is also repetitive and regular, but does not possess

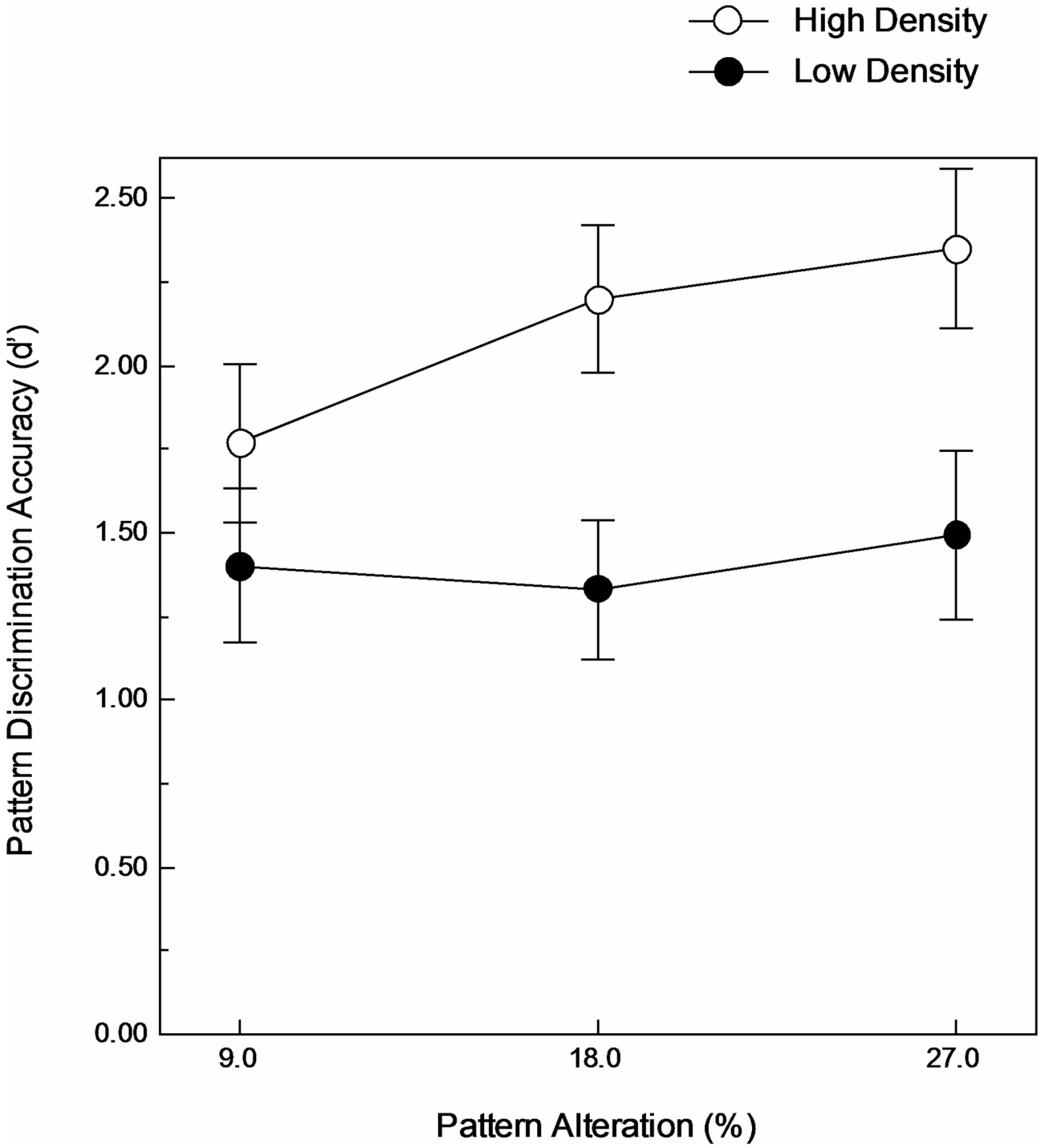

Fig. 6. Experimental results. The observers' overall pattern discrimination performance is plotted as functions of pattern density and the magnitude of pattern alteration. The error bars indicate ± 1 SE.

prominent directionality). Clusters B and G/H are located at opposite ends of the x-axis determined by MDS (the dimension corresponding to random textures versus repetitive/non-random/regular textures). The research of Rao and Lohse[24] demonstrates that human observers are perceptually sensitive to regularity/repetitiveness and deviations from it. In our current experiment, observers were asked to discriminate between perfectly regular visual patterns that tile the plane and patterns that had been altered so that the regularity/repetitiveness was reduced by varying degrees, depending upon the experimental condition (i.e., 9% pattern element alteration, 18%, & 27%). Rao and Lohse[24] concluded by saying (p. 1667) "In this paper we have identified the three most significant dimensions of texture based on a study of 20 subjects over 56 texture images". The observers in our current experiment thus discriminated texture patterns that varied along one of the fundamental dimensions of human texture perception.

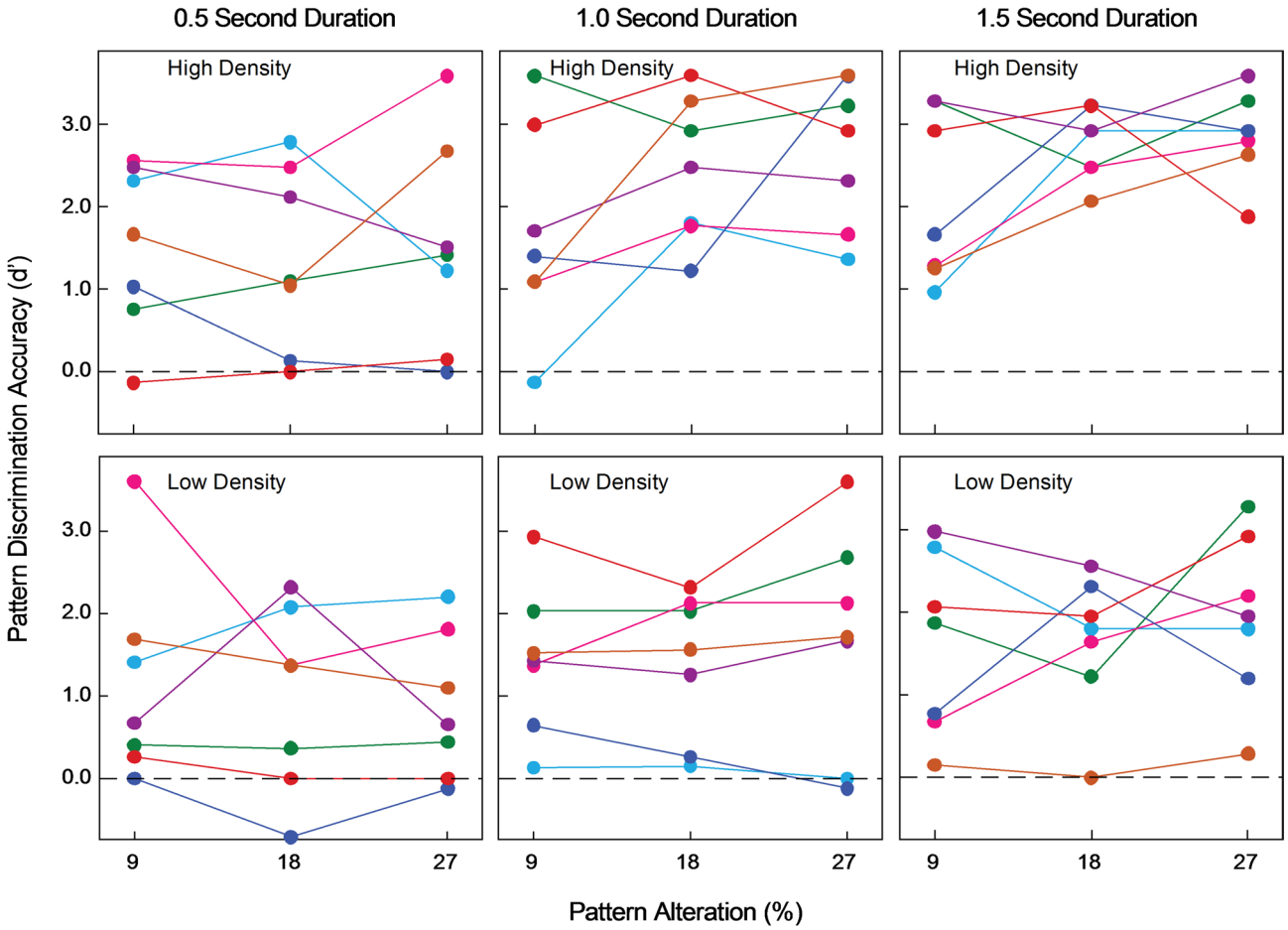

Fig. 7. Experimental results (d' values) for all individual observers in all experimental conditions (pattern density and pattern alteration magnitude were within-subjects variables, while stimulus duration was a between-subjects variable). These plots illustrate the large amounts of interobserver variability that occurred *within* the three groups of observers (i.e., within the three columns). For each combination of stimulus duration and pattern density, the observers' pattern discrimination performance is plotted as a function of the amount of pattern alteration. The dashed lines indicate chance levels of discrimination performance. Some observers who performed at near chance levels for the low density patterns (e.g., the observer indicated in orange in the 1.5 s duration condition and the observer indicated in light blue in the 1.0 s duration condition) performed well for the high density patterns, especially at the two highest pattern alteration magnitudes.

As reviewed in the previous paragraph, there is good behavioral evidence of a sensitivity of human observers to pattern regularity/repetitiveness[24]. There is also human neurophysiological evidence from functional magnetic resonance imaging (fMRI) data (see Kohler, Clarke, Yakovleva, Liu, & Norcia[25]). In contrast to cortical area V1, where neurons respond to basic image features such as oriented contours and color[26,27], Kohler et al.[25] have demonstrated that extrastriate cortical areas such as V3, V4, VO1, and the LOC (lateral occipital complex) in the human visual system are sensitive to the regularity/repetitiveness of periodic patterns that tile the plane. Thus, there are dedicated mechanisms within the human visual system that may play a role in the perception and/or behavioral detection of periodic patterns, such as those utilized in the current study.

There is a small amount of preexisting research (Landwehr[28]) involving discrimination of periodic patterns that tile the plane. On any given trial in Landwehr's Experiment 1, he showed observers four textured patterns that tile the plane. One differed from the other three in terms of the underlying pattern type (e.g., in Fig. 4 of Landwehr[28] the plane periodic pattern type of the target was pm, while the three distractors had a pattern type of p1; for a detailed explanation of plane periodic pattern types, see Schattschneider[29] -- in short, p1 patterns consist of repeating stimulus elements that only translate, while pm repeating patterns contain both translation and mirror reflections) -- the observers' task was to simply detect which pattern of the four was the target. This task obviously requires observers to differentiate between different types of periodic patterns. While most of Landwehr's observers performed the periodic pattern discrimination task at above chance levels, his task was quite challenging -- the overall d' value (after excluding the data of about 7% of his observers for low performance) of his observers was a modest 1.27. The performance of our observers in the current study for the high-density patterns was much higher (the overall d' value for the high-density patterns for our observers was 2.11).

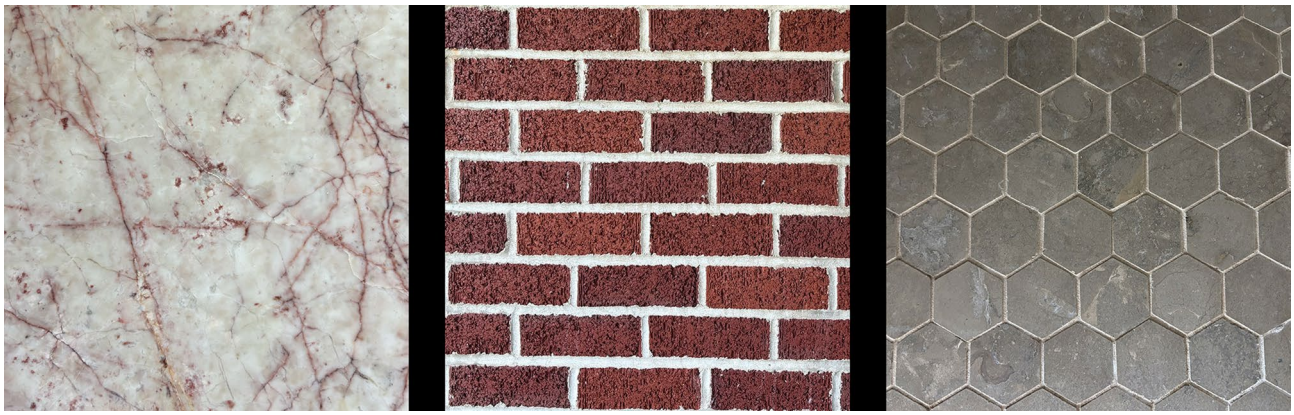

Fig. 8. Examples of textures belonging to three of the eight clusters of textures identified by Rao and Lohse[24]. These photographs were taken by the first author (J.F.N.) using an iPhone 15 camera. The texture (marble) on the left would belong to cluster B and possesses high randomness and very low regularity/repetitiveness. The brick (middle image) texture and hexagonal tile (right image) texture would belong to clusters G and H, respectively. Clusters G and H textures possess high regularity and repetitiveness; what distinguishes clusters G and H textures is directionality -- for example, the brick texture has more directionality than the hexagonal tile texture. Our unaltered stimulus patterns that tile the plane (Fig. 4) possess high repetitiveness/regularity; the repetitiveness/regularity of our altered stimulus patterns (Fig. 5) would be less, depending upon the amount of pattern alteration on any given trial (i.e., 9, 18, or 27%).

Even though both their stimuli and topic/motivation were quite different from ours, Bruce and Morgan[30] (also see Experiment 2 of Westphal-Fitch et al.[31]) used the same task as the one adopted in the current study -- to determine on each trial whether a pattern was "regular" or "altered". The "regular" stimuli used by Bruce and Morgan were not periodic tilings of the plane (our stimuli), but were either two patterns that were bilaterally symmetric or two exact copies of a pattern that differed only by a translation (see Fig. 1 of Bruce & Morgan). These authors concluded (p. 239) "Small departures from symmetry near the midline were much easier to detect than the same violations in a repeated pattern, but there were no differences where the violation was at the edge of the pattern… both symmetry and departures from it are easier to detect than repetition, even when the nature of the violation is random". Our goal was not to study symmetry, but we were nevertheless happy to adopt the general task employed by Bruce and Morgan.

The largest effect obtained in the current experiment (the effect of pattern density, see Fig. 6) is very similar to phenomenal demonstrations published by Bela Julesz[11] in 1975. Figures 9 and 10 of the current article represent our current renderings of the type of stimuli described by Julesz[11]. Consider our Fig. 9 and the middle panel of the figure of Julesz[11] at the bottom of his page 35 -- in both of these images, each of the four quadrants contains the same exact pattern (i.e., the images contain a 2×2 array of the same randomly-generated pattern), but it is very difficult (almost impossible) to see the repetition of the pattern. Now consider our Fig. 10 (separate examples are shown in the left and right panels) and the figure of Julesz[11] at the top left of his page 36 -- these images show a 5×5 array of identical patterns. Unlike the analogous 2×2 array, the repetition of the pattern within these 5×5 arrays is easy to see. Julesz[11] therefore concluded (p. 34) that "if the periodic distance is sufficiently reduced, the periodicity of random arrays can be perceived immediately". Our effect of density (performance for high-density patterns is much higher than for low-density patterns, see Fig. 6) agrees with the phenomenal demonstration provided by Julesz. In our high density patterns (compare the right and left stimulus examples in our Fig. 4), the periodic distance (as Julesz refers to it) is much smaller, and therefore (according to Julesz's conclusion) the repetition of the periodic patterns is much more visible (leading to much higher discrimination performance on the part of our observers).

Conclusions and limitations

In this evaluation of the ability of human vision to detect irregularities in periodic tiling patterns, we find that performance is quite good, as long as the stimulus limitations noted by Julesz[11] are observed. Human observers can reliably discriminate between perfectly regular periodic patterns that tile the plane and those that have been altered, as long as the periodic distance between repetitions of the basic (i.e., generating) pattern is sufficiently small. At the same time, large individual differences in performance occurred (see Fig. 7). The cause/reason for these individual differences in discrimination performance for the same experimental conditions remains unknown. One important goal for future research will be to explore and hopefully understand such individual differences in visual pattern discrimination. It is possible that there is some actual effect of stimulus duration, but our relatively small sample size and choice of between-subjects manipulation of this variable prevented us from detecting it. Future research evaluating duration as a within-subjects variable or a larger sample size will be needed to assess the potential effect of duration.

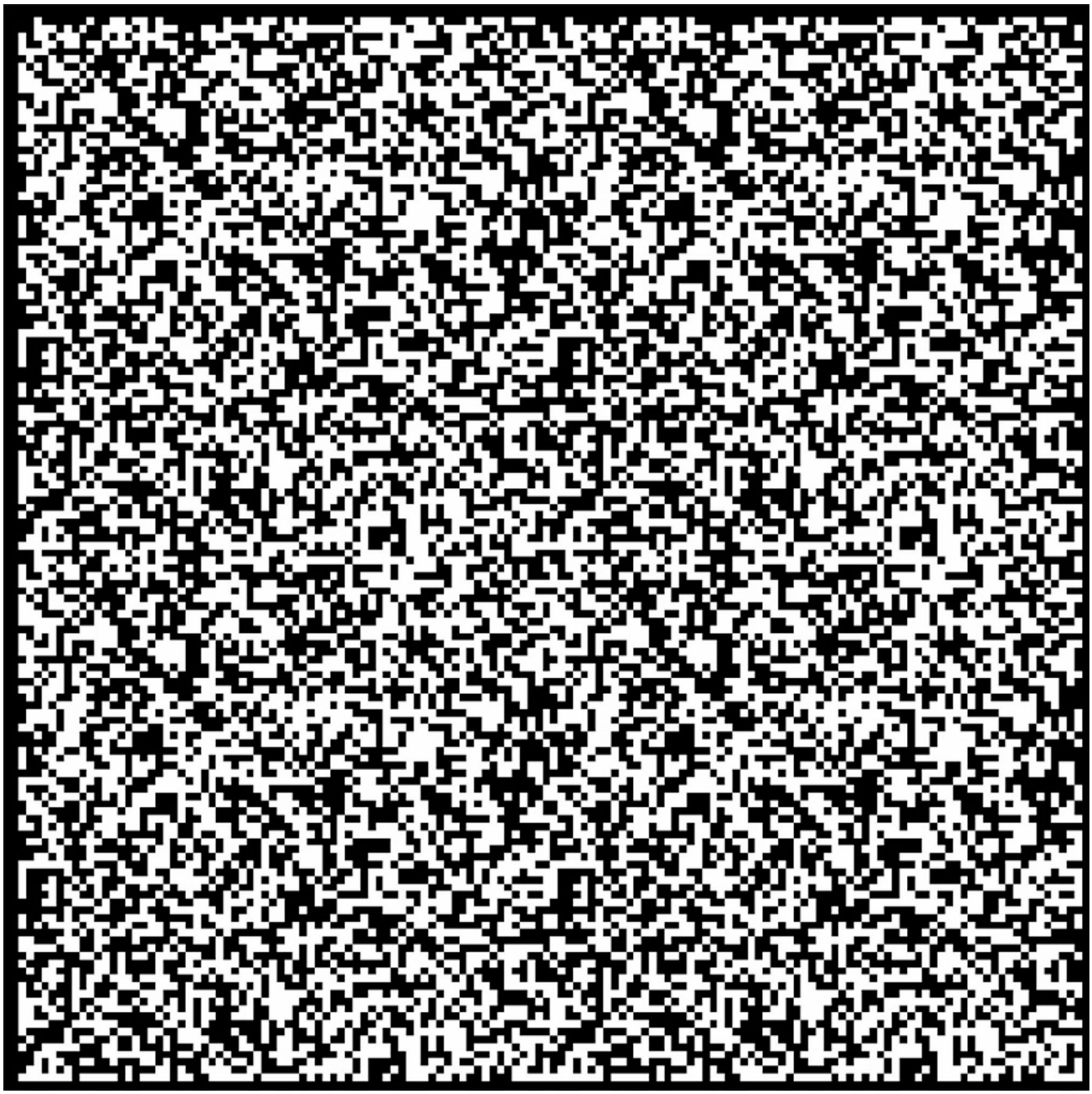

Fig. 9. The four quadrants of this image (2 × 2 array) contain exactly the same randomly generated pattern. The repetition of this pattern is very difficult, almost impossible, to see.

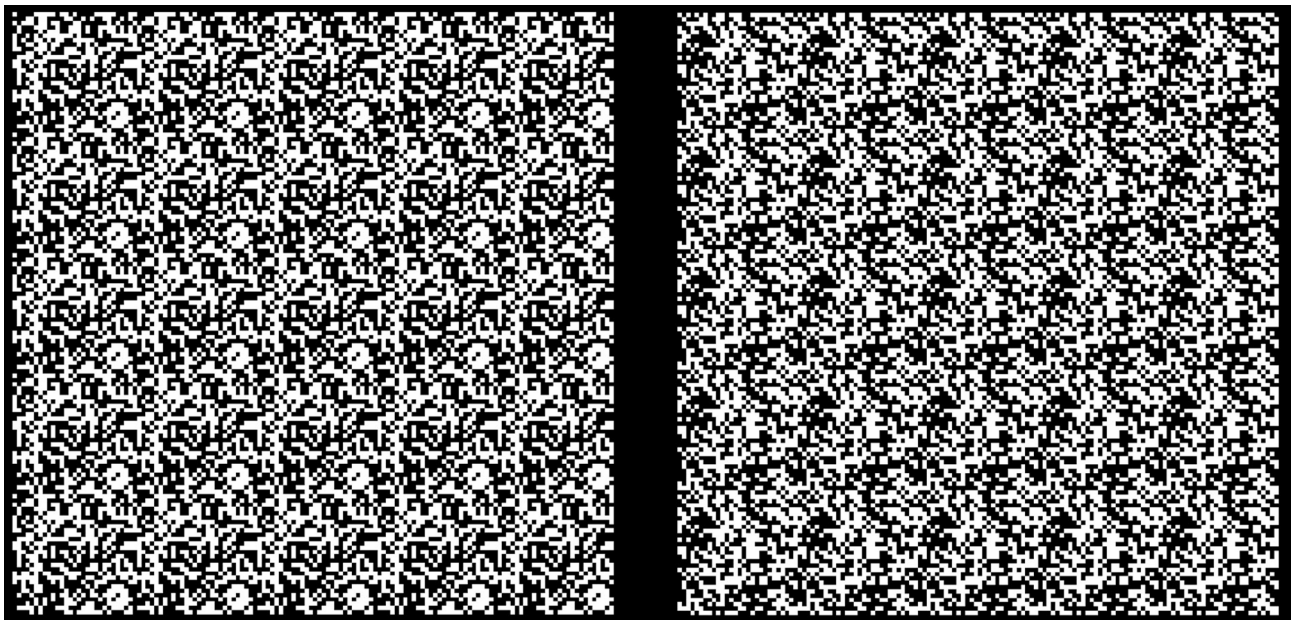

Fig. 10. In each of these two images (left and right) there are 25 repetitions (5 × 5 array) of a randomly generated pattern. The repetition of the pattern within each image is very easy to see (because of the smaller spatial scale over which the basic pattern repeats, compare with the larger scale in Fig. 9).

Data availability

The datasets generated and analyzed during the current study (d' values for all individual observers in all experimental conditions) are included in Figure 7 of this article.

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Author contributions

J.F.N. developed the study concept. J.F.N. and M.C. developed the study design. J.F.N. was responsible for stimulus preparation. Data collection was performed by J.F.N., M.C., Y.M., E.H., and A.S. The data analysis was performed by J.F.N. The figure preparation was performed by J.F.N. J.F.N. wrote the manuscript. All authors reviewed the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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